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Study of terahertz radiation from narrow bandgap semiconductors: InAs and InSb

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Abstract — We investigated THz radiation from narrow bandgap semiconductors: n-type, p-type InSb and InAs were investigated using a time-resolved THz detection system. As a reference, THz radiation from InP (a wide bandgap semiconductor) was also measured. From the polarity of the waveforms we concluded that the ultrafast build-up of a photo-Dember field is the main emission mechanism for both InAs and InSb.

I. INTRODUCTION

It is known that THz radiation can be generated by irradiation of ultrashort laser pulses on semiconductors surface [1]. Besides optical rectification of ultrafast laser pulses [2], two processes are known to contribute to the THz radiation in bulk semiconductors. In semiconductors with a wide bandgap, such as InP, the generation of THz radiation is based on the ultrafast screening of the surface depletion field by the photoexcited carriers [3]. For the narrow bandgap semiconductors, on the other hand, the depletion field is generally not so strong, and the emission of THz radiation due to the depletion-field screening is not expected to be efficient. However, for the narrow bandgap semiconductors, such as Te and PbTe, it have been shown that the ultrafast build-up and relaxation of the photo-Dember field can be an efficient mechanism for generation of THz radiation. It is because that the high temperatures of photo-excited carriers due to the large excess energy and the small absorption depth (~ 100 nm) for the near infrared light cause a strong surface field by the much faster diffusion of electrons than that of holes at the sample surface (photo-Dember effect) [4]. InSb is a narrow bandgap semiconductor, that is a unique and important material because of its high carrier mobility and small bandgap energy (Table 1). It is expected that THz emission efficiency of InSb should be comparable to or better than that of InAs because of its smaller effective electron mass and larger electron mobility than that of InAs. However, in a previous reports, we observed that the radiation power of n-InSb is approximately one-hundredth of n-InAs at room temperature [5]. In order to explain this difference, it is crucial to study the radiation mechanism of InSb and InAs.

In this work we investigated the azimuthal angle dependence of the THz radiation amplitude and THz radiation waveforms of n-type, p-type InSb and InAs using a time-resolved detection system in the same experimental condition. From the polarity of the waveforms we concluded that the ultrafast build-up of the photo-Dember field is the main radiation source for both InAs and InSb.

II. EXPERIMENTAL

The experiments were performed using a mode-locked Ti: sapphire laser pulses with an 80-fs pulse width and the 78-MHz repetition rate at a 800-nm wavelength. The laser beam was split into two parts. One part with an

Table 1: Sample poperties

Sample	InSb	InAs	InP
Bandgap: E_g	0.17eV	0.36eV	1.34eV
Electron mobility: μ_e	76000 $cm^2V^{-1}s^{-1}$	30000 $cm^2V^{-1}s^{-1}$	4000 $cm^2V^{-1}s^{-1}$
Hole mobility: μ_h	3000 $cm^2V^{-1}s^{-1}$	240 $cm^2V^{-1}s^{-1}$	650 $cm^2V^{-1}s^{-1}$
Electron mass: m_e^*	$0.0133m_e$	$0.028\ m_e$	$0.07\ m_e$
Hole mass: m_h^*	$0.18\ m_e$	$0.33\ m_e$	$0.40\ m_e$
Surface depletion field: $\phi_s \sim E_g/2$	0.085eV	0.18eV	0.67eV
Refractive index ($\lambda = 800nm$)	4.47	3.73	3.47
Refractive index (f = 1THz)	1.93	3.78	3.52
Absorption depth: d ($\lambda = 800nm$)	94 nm	142 nm	305 nm
Excess Energy: E (eV/T)	1.38eV/10500K	1.18eV/ 9000K	0.21eV/5000K
Electron temperature: T_e	9800K	8300K	1250K
Hole temperature: T_h	700K	700K	250K

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averaged power of 80 mW illuminated the sample surface at an incident angle of 45° to generate THz radiation. The other part (10 mW) gated the photoconductive dipole antenna detector to measure the THz radiation waveform. The polarization of the excitation laser beam was p-polarized and the direction of the dipole antenna was also in the same direction. The excitation laser pulses were focused onto the n- and p-InSb and -InAs surface to a spot size with a diameter less than 1 mm. The THz radiation from the sample in the optical reflection direction is collected and focused on the antenna detector with a pair of off-axis parabolic mirrors. The time-resolved waveforms of the radiation were obtained from the DC photocurrent in the antenna detector by varying the delay time between the pumping and gating pulses. The detector is a dipole photoconductive antenna having a length of 30 μm fabricated on low-temperature-grown GaAs. All experiments were performed at room temperature.

We used samples of a n- and p- InSb (100) with a residual carrier concentration of n ~ 10^{16} cm^{-3}, of a n-InAs (111) and p-InAs (100) with a residual carrier concentration of n ~10^{18} cm^{-3}, and of a n- and p- InP (100) with a residual carrier concentration of n ~10^{18} cm^{-3}.

III. RESULTS AND DISCUSSION

Figure 1 shows the azimuthal angle dependence of the THz radiation in the present experimental configuration (a) for n- InAs (111) and (b) for n- InSb (100). Taking the surface normal as x-axis and the reflection plane as x-y plane, the electronic polarization induced in the semiconductors due to the optical rectification for (111) and (100) surface is expressed by Eq. (1) and (2), respectively:

$$P = d_{14}E^2 \begin{pmatrix} -\frac{1}{3}\cos^2\phi + \frac{2}{\sqrt{3}}\sin^2\phi \\ \frac{2}{\sqrt{6}}\cos^2\phi\cos3\theta - \frac{2}{\sqrt{3}}\cos\phi\sin\phi \\ \frac{2}{\sqrt{6}}\cos^2\phi\sin3\theta \end{pmatrix} \quad (1)$$

$$P = d_{14}E^2 \begin{pmatrix} \cos^2 2\phi\sin2\theta \\ \sin2\phi\sin2\theta \\ \sin2\phi\cos2\theta \end{pmatrix} \quad (2)$$

Here, ϕ is the angle between the surface normal and the excitation laser beam inside the sample, and θ is the azimuthal angle around x-axis. As the THz radiation was detected in a reflection geometry for p-polarization, the observed THz field amplitude is expected to be proportional to

$$-p_x\sin\phi_{THz} + p_y\cos\phi_{THz}, \quad (3)$$

$$\sin45° = n_{THz}\sin\phi_{THz},$$

where ϕ_{THz} is the refraction angle for THz radiation at the interface of the sample surface and air, and n_{THz} is the refractive index of THz radiation. For the laser wavelength of 800 nm, ϕ is 10.9°, 9.0°, and 11.8° for InAs, InSb, and InP, respectively. For THz radiation ϕ_{THz} is estimated to be 10.9°, 21.5°, and 11.9° for InAs, InSb, and InP, respectively. Using these values, the angle
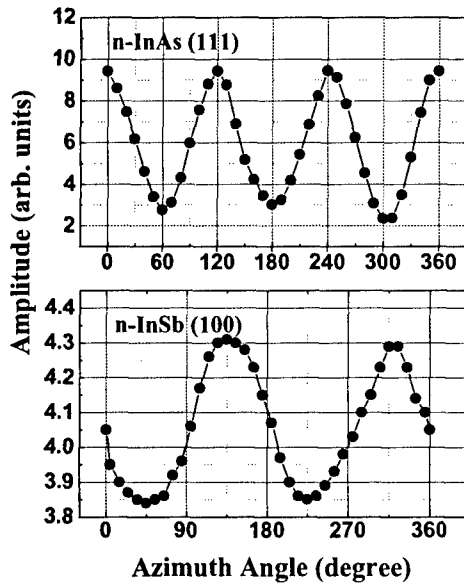

Fig.1: Azimuth angle dependence of THz radiation amplitude from semiconductors with (a) n-InAs (111) and (b) n-InSb (100) surface at a 45° incident angle of the excitation light on the sample. The solid line is only to guide the eyes.
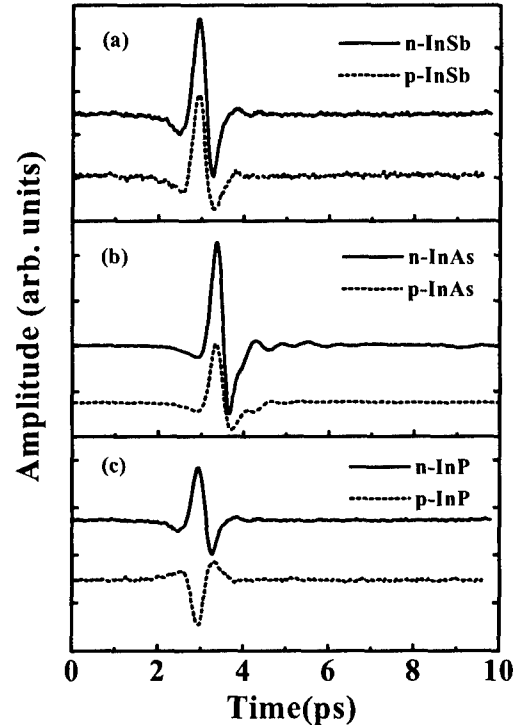

Fig. 2: Time-domain waveforms of the THz radiation from n- and p- (a) InSb, (b) InAs and (c) InP.

dependence of the radiation amplitude thus can be written as follows:

$$E \propto 0.773\cos 3\theta - 0.153 \quad \text{for InAs (111),} \quad (4a)$$
$$E \propto 0.182\sin 2\theta \quad \text{for InAs (100),} \quad (4b)$$
$$E \propto -0.069\sin 2\theta \quad \text{for InSb (100),} \quad (4c)$$
$$E \propto 0.199\sin 2\theta \quad , \quad \text{for InP (100).} \quad (4d)$$

As shown in Fig.1 the angle dependence of the radiation has a dc offset, which is attributed to the real surge current at the sample surface except for InAs (111), for which both the nonlinear process and the surge current can contribute to the dc offset. To suppress the component of THz emission resulting from optical rectification, we measured the THz radiation at azimuthal angle 26° for n-InAs (111), and 90° for p-InAs (100), and n-, p-InSb (100), where the components due to the optical rectification effect is expected to be null according to Eq. (4a)~(4d). The results are shown in Fig. 2(a) and 2(b). We also show the THz radiation waveforms of n- and p-InP in Fig.2(c) for comparison. It is known that the generation of THz radiation from InP originates mostly from the ultrafast screening of the surface depletion field by the photo-excited carriers [3]. The THz radiation due to the screening of the surface depletion field flips its polarity for the different type of doping due to the reversal of the direction of the surface depletion field, as is clearly shown in Fig.2(c). However, when the THz radiation is emitted by the ultrafast build-up and relaxation of the photo-Dember field, which originates from the different diffusion coefficients of electrons and holes, the polarity of the THz radiation remains the same for n-type and p-type semiconductors because the diffusion coefficient of electrons is always bigger than that of holes due to the small effective mass, irrespective to doping type of the semiconductor. The THz waveforms of n-, p-InSb and -InAs have the same polarity as shown in Fig.2 (a) and (b). This indicates that the excitation mechanism for the THz radiation in InSb and InAs is due to the ultrafast build-up and relaxation of the photo-Dember field. The radiation amplitude of the n-type InAs and InSb is a little larger than that of p-type. We suggest that there might be an enhancement of THz radiation due to the surface depletion field because the direction of the surface depletion field and the photo-Dember field is the same for n-type semiconductors.

By considering the sample properties, as listed in Table 1, we are able to have more insight into the THz emission mechanisms. The surface depletion field of InAs and InSb should be much smaller than that of InP due to their small band gap energy. Consequently, the screening of surface depletion field should not be a strong source of THz radiation for InSb and InAs. On the other hand, because the photo-Dember field results from the different diffusion coefficients of electrons and holes, the build-up of the Dember field should be large for semiconductors with higher electron mobility. The short absorption depth of the laser light for the narrow bandgap semiconductors also helps to enhance the photo-Dember field because the photo-Dember field is proportional to the gradient of the carrier density. For 800-nm light the absorption depth of InAs and InSb is calculated to be 94 nm and 142 nm, while that of InP is 304 nm, respectively. In addition, the electron mobility and the excess energy of InSb and InAs is much bigger than InP due to the small effective mass and the narrow band gap. All these conditions are suggestive of a large Photo-Dember field for InAs and InSb with the optical excitation. Thus, we conclude the main source of THz radiation for InAs and InSb is the photo-Dember field, not the screening of the surface depletion field.

IV. CONCLUSION

By observing the polarity of the THz radiation from n- and p- InSb and -InAs, the main excitation mechanism of the THz radiation in the investigated narrow-band gap semiconductors, that is InSb and InAs, was concluded to be the ultrafast build-up and relaxation of the photo-Dember field. The detailed analysis of the ultrafast build-up of photo-Dember field at the narrow bandgap semiconductors will be is given in the Conference.

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